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Dynamic fault simulation of wind turbines using commercial simulation tools

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Abstract - This paper compares the commercial simulation tools: PSCAD/EMTDC, PowerFactory, SIMPOW and PSS/E for analysing fault sequences defined in the Danish grid code requirements for wind turbines connected to a voltage level below 100 kV. Both symmetrical and unsymmetrical faults are analysed. The deviations and the reasons for the deviations between the tools are stated. The simulation models are implemented using the built-in library components of the simulation tools with exception of the mechanical drive-train model, which had to be user-modeled in PowerFactory and PSS/E.

Index terms – Wind turbine, squirrel cage induction generator, simulation tools, fault analysis, unsymmetrical faults, wind farm, grid code, transient fault response, RMS simulation.

I. Introduction

Today, wind power penetration is getting larger and larger, speaking of installed power capacity (MW) and electrical energy (GWh) as well as the share of wind power of total electricity production in power systems. The power system operators have set the rules, grid codes, for all the production and consumption connected to the grid. Over the recent years special rules and requirements have been set for wind power production as well, although at the moment they are based on conventional production requirements. Because wind power penetration has been negligibly small in the past, there have been no models of wind turbines or wind parks available for power system studies. In load flow calculations the wind power does not differ remarkably from conventional production units, but transient models are now needed for evaluating whether the requirements set in the grid codes are, and can be, met or not.

Nowadays, a variety of simulation tools for power system analysis is available. Some of them have started from different bases to solve different problems. Different instances have chosen their tool/tools based on their needs at the time of the purchase. The trend is that the software companies try to expand their programs to cover more and more aspects of power system analysis. Many programs therefore have overlapping functionalities today. The documentation rarely gives a clear definition of the limitations of the programs. Hence, it can be difficult for users to select the tool most suitable for solving their specific problems, or to be sure the simulation tool in their use can cope wind power modeling and gives reliable results. Transmission system operators (TSO), distribution network operators (DNO), wind farm operators, and turbine manufacturers all may have different kinds of needs for wind power models for simulations. TSOs and DNOs may want to study the system or subsystem operation wind power production as part of it, where as wind power operators and manufacturers are likely to be interested in more detailed turbine behavior. Many users may be tied firmly to the simulation tool they are using, as their models, developed and expanded over years, may be set up for this particular tool as well as the know-how is bound to it. In addition, the simulation tool may have worked fine for them considering conventional power production. It is a challenge for simulation tool developers to provide wind power models that cover the needs of the software user, but still keep the models simple and straight forward enough not to burden the user or the solver too heavily. All commercial simulation tools may not have extensive wind power model libraries with verified model as standard features today, although some models, verified or not, for different simulation tools are provided. Not all wind turbine manufactures, or wind farm owners and operators, have been capable of providing satisfactory dynamic models to the TSO [1][2]. In this paper, the standard models of simulation programs in question, are being used for comparison of simulation tool ability of modeling and simulation of wind power for short-term analysis.

Wind power is different from conventional electricity production in many ways. Wind turbine or wind park production is based on momentary wind conditions at the site, and therefore the production varies in hourly bases, and at the same time it fluctuates due to turbulence and uneven wind field distribution in second bases. The wind power production can not be predicted with absolute reliability and the variations of production can be fairly large within hours. Due to the nature of wind power, the wind turbine generators are not synchronous generators directly connected to the grid, as opposition to conventional regulating power.

The wind power generating units are fairly small compared to conventional power plants, but may compose large parks of sizes comparable to reasonably large conventional power plants. In addition to wind fluctuations, the production from wind turbines is dependent on the turbine aerodynamics and mechanics, which both play a role in case of a disturbance.

Dynamic simulations of wind turbines in different power system simulation tools have been presented in several papers from previous works. Some of the simulation tools that can be mentioned, are PSS/E [3] and [4], PowerFactory [5], SIMPOW [6], PSCAD/EMTDC [7] and many others. Those papers are mostly aimed at presenting the study related with wind turbines in power systems using the available tools rather than providing the detailed reasons of selection and the review of the tools. Exception to this is [3], where some comments of tool in wind power study are addressed in rather detail. However, papers that solely provide reviews of the tools suitability in wind power study and comparisons among them, are rarely found.

In this paper a comparison of abilities and performance of four common commercial simulation programs, PSCAD/EMTDC, SIMPOW, PowerFactory and PSS/E are presented regarding their suitability for simulations involving wind power within a short-term period of analysis.

EMTDC (**E**lectro-**M**agnetic **T**ransients including **DC**) was initiated by Manitoba Hydro in Canada. In mid-70's the earliest versions of the software were used by Manitoba Hydro for HVDC system simulations. EMTDC simulations were carried out by using a command line approach until the graphical user interface, PSCAD (**P**ower **S**ystems **C**omputer **A**ided **D**esign) for EMTDC, was developed by Manitoba HVDC Research Centre in late 80's. At first, PSCAD was used to improve coding reliability and make working with EMTDC easier. Some years after its initiation, PSCAD was commercialized. According to the software developer [8], in early years of 21st century the "next generation" of the software was developed and the latest package available today is PSCAD/EMTDC V 4.1.1. PSCAD/EMTDC is nowabays also referred simply as PSCAD.

ABB Power Systems AB, Sweden, started in the early 60's to develop internal programs to solve specific problems. The experiences gained over these years led to the development of SIMPOW (SIMulation of POWer systems) in 1977 [9]. SIMPOW covers a wide field of applications in power system analysis with built-in library models from power electronics like HVDC and FACTS components, generators, generator control systems, loads to transformers and line models, focusing on time domain dynamic simulation and analysis in the frequency domain. The input data is entered using input files, and based on the input data, the grid topology can be displayed graphically after solving load-flow. In 2004 SIMPOW development and administration was transferred from ABB to Swedish company STRI AB. Latest version available is SIMPOW 10.2. [10]

DIgSILENT (**DIg**ital **SI**mu**L**ator for **E**lectrical **N**e**T**work) development started in Germany in 1976. According to [11], the DIgSILENT Version 7 was the world's first power system analysis software to have integrated graphical one-line interface. In 1993 the DIgSILENT GmbH consulting and software company initiated the PowerFactory software by applying improved solution algorithms and advanced software technology incorporating an object-oriented database to improve DIgSILENT version 10.31. The "new generation" of the PowerFactory software was released in 1997 and was the first version providing the required product stability. Today the latest version available is PowerFactory Version 13.1.

The American software PSS/E (**P**ower **S**ystem **S**imulator for **E**ngineering) was introduced in 1976 by Power Technologies Inc – today known as consulting engineering company Siemens Power Technologies International, LLC (Siemens PTI). The latest release of the program is PSS/E-30 which according to PTI [12], is the most significant update on their product they have ever had. In this version Microsoft compliant graphical interface in load flow is a new feature.

II. Background for the Choice of Simulation Cases

When studying power systems phenomena using simulation tools, the analysis is usually divided in subcategories being dependent on the dynamic characteristics of the phenomena being analysed. Some power system simulation tools have their strength in implementing large complex grid topologies usually at expense of the level of detail for each power system component, while others have focused on the component detail usually with limitations on topology of the grid interfacing the component. This is based on the original problem the program was designed to analyse. It is important, with the detailed knowledge of the components as part of the whole system, determine if the component main characteristic can influence the overall characteristic. Hence, an overall view of the system response can be obtained. This has been discussed in the recent years with the basis in wind turbine modeling and the suitability of the tools for analysing the electrical dynamic phenomena of wind power generation. Still, with software companies developing their tools and adding more features and more details to their models, the borders and the limitations of the program usage must to some extent be redefined.

Table 1 gives a rough overview of the investigated programs and their designed capability of analysing relevant problems.

Table 1 Abilities of each simulation program

	EMT*	EMD**	SSA***
PSCAD	Yes	Yes	No
SIMPOW	Yes	Yes	Yes
PowerFactory	Yes	Yes	Yes
PSS/E	No	Yes	Yes

*Electromagnetic transients
**Electromechanical dynamic analysis
***Steady state analysis

This paper discusses the response in the short-term dynamics region. Short-term dynamic analysis is mainly connected to electromechanical behavior, but can be extended to include transient phenomena.

The Danish TSO has given new grid requirements for connecting wind farms to the grid at voltage level below 100 kV [16]. The requirements are set for installations above 1.5 MW output power. Grid code requirements concerning grid faults were chosen to be studied in this paper. For the Danish grid code requirements the following faults are defined with time sequences:

3-phase short circuit: short circuit lasting 100 ms

2-phase short circuit with/without earth fault: short circuit lasting 100 ms followed by a new short circuit 300…500 ms later, also lasting 100 ms.

The wind turbines must be able to cope with these kinds of grid disturbances without disconnection. Ride-through requirements as proposed in this grid code, follow the trends for TSO requirements in grids worldwide where wind-power penetration is increasing.

These requirements also make it relevant to study differences in the current commercial software packages. The generator performance (trip or no trip) is dependent on the transients that the generator "sees" in the short-term time scale. Therefore, an accurate representation is to some extent needed.

In this paper the simulations and analyses are concerned with a wind farm connected to the 50 kV grid through a radial connection. The fault is applied to the connecting 50 kV grid. The reason for this is twofold:

First, the faults defined in Eltra's grid code are defined at transmission level; that is at the level above 100 kV.

Second, a fault in the interconnection of the wind turbine installation is not interesting as the fault would mean a disconnection of the farm. Even if the fault is more severe for the wind turbine components, the interaction with the grid is needed for a more realistic case relevant to the defined grid codes. Furthermore, the protection of the wind farm itself is not the aim of the analysis done in this paper.

The fault on the high voltage side of the wind farm connecting transformer is therefore considered more realistic and interesting considering wind farm-grid interaction.

When considering protection and loading of power systems, the 3-phase fault is considered worst case in the sense that it gives the highest stationary short circuit current contribution and therefore the highest thermal strain on the power system components. The 3-phase short circuit current normally defines the grid protection characteristic.

The reason for choosing a 2-phase fault is mainly related to the fact that unsymmetrical faults are more common in the grid, and it is therefore interesting to see how the simulation programs handle the analysis of unsymmetrical fault situations. These faults may also have a larger influence on the generator control system; however, studying the control response is not the main topic of this paper. The control system may have significant differences in the different wind turbine designs.

III. Test System Model

For comparison of the tools, a benchmark case has been implemented. The objective of the simulations is twofold: First, the implementations reveal how easily a model can be build in the respective tools and which types of simulations can be carried out with them. Second, the outputs can be compared to point out differences in the dynamic behavior of the models implemented in the different tools.

A. The original system

The synthetic test system presented in [5], which has been made on the basis of a single wind turbine in the wind farm Hagesholm in Eastern Denmark, is chosen. Fig. 1 presents the test system as it is described in [5].

G_{50}: Thevenin equivalent of the distribution network

T_{SS}: 50/10.5 kV YNΔ5 coupled transformer modeled as a T-equivalent without saturation and iron losses. The tap changer is not considered

Ca_{col}: Cable modeled as a π-equivalent

T_{WT}: 10.5/0.96 kV ΔYN5 coupled transformer modeled like T_{SS}

G_{WT}: Wind turbine with an induction generator modeled as a single cage T-equivalent without saturation, and a mechanical Two mass model

C_{WT}: Δ coupled capacitor battery including resistive losses

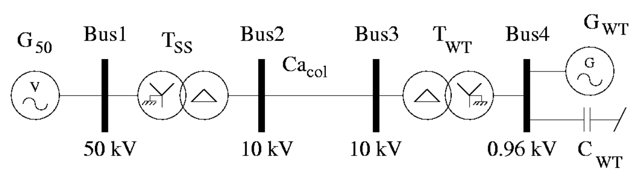

Fig. 1 Test system with a wind turbine connected to a 50 kV distribution network through a 10 kV cable

The mechanical model of the turbine, shown in Fig. 2, consists of two moments of inertia, stiffness and an ideal gear-box. The torque from the wind is assumed to stay constant during the simulations. The parameters can be found in the appendix.

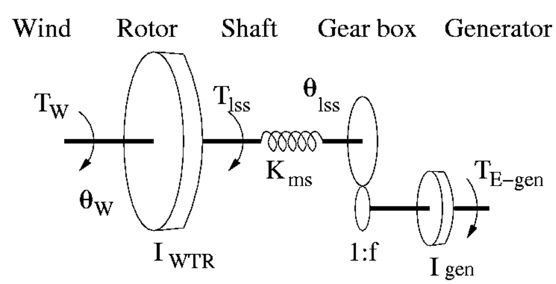

Fig. 2 Two mass mechanical model of the wind turbine

B. Extension for simulations of unsymmetrical faults

In [5] only 3-phase faults were simulated. Hence, no information on the zero sequence of the system is available for the benchmark system.

Fig. 3 shows the equivalent circuit for stationary short circuit calculations corresponding to the positive and negative sequence of the system (except that the phase shift of the transformers in the negative sequence has the opposite sign). The capacitance of the cable and the capacitor bank only has minor influence in the calculation of the short circuit currents. The same applies for the magnetizing reactances of the transformers and the induction generator. Since the saturations are not considered, the subtransient reactances of the transformers and the generator are equal to the transient reactances.

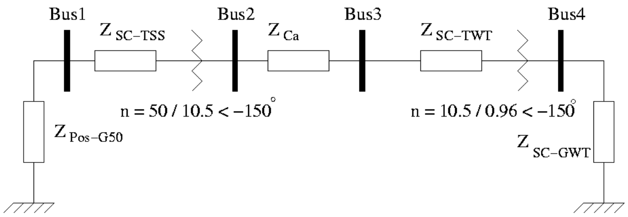

Fig. 3 Short circuit equivalent of the positive and negative sequence

According to [13] the zero sequence impedance of a YNΔ coupled transformer is equal to the short circuit impedance in parallel with the magnetizing reactance and the iron loss resistance. The two last terms can be neglected. Consequently, the zero sequence impedance of transformers seen from the YN side is modeled with the short circuit impedances of the positive sequence. Since the generator is Δ coupled it will not contribute to the zero sequence. The capacitance of the cables will only play a minor role in case of a short circuit. The zero sequence of the Thevenin generator is assumed to be equal to the positive sequence. This gives the equivalent circuit shown in Fig. 4 for the zero sequence.

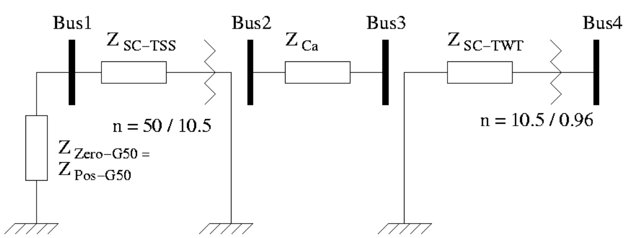

Fig. 4 Short circuit equivalent of the zero sequence

C. *Resonant frequency*

When the system is subjected to a sudden change, an oscillation between the capacitances and the inductances will occur. According to [5] a good estimate of the dominant eigenfrequency can be found by disregarding the shunt reactances of the transformers and the generator, the shunt capacitances of the cable, and the resistances.

For the 3-phase case this gives the simplified equivalent shown in Fig. 5, where the inductances have been converted to the 1 kV level.

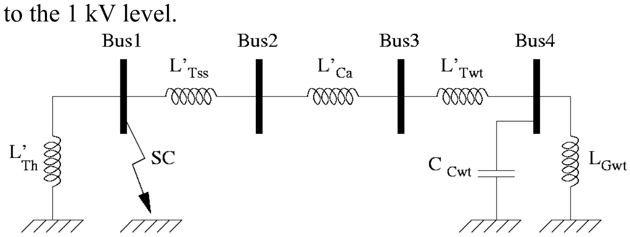

Fig. 5 Simplified equivalent circuit for calculation of oscillation frequency

As long as the short circuit is active, the eigenfrequency can be calculated as in (1).

$$f_{eig-sc} = \frac{1}{2\pi\sqrt{C_{Cwt}\cdot\left(\left(L'_{Tss}+L'_{Ca}+L'_{Twt}\right)\parallel L_{Gwt}\right)}} \tag{1}$$

When the short circuit is cleared, the inductance of the Thevenin generator must also be taken into account, which gives the expression in (2).

$$f_{eig} = \frac{1}{2\pi\sqrt{C_{Cwt}\cdot\left(\left(L'_{Th}+L'_{Tss}+L'_{Ca}+L'_{Twt}\right)\parallel L_{Gwt}\right)}} \tag{2}$$

With the data from the appendix and appropriate conversions this gives:

$$f_{eig-sc} = 271.3\,\text{Hz} \tag{3}$$

$$f_{eig} = 263.7\,\text{Hz} \tag{4}$$

In the unsymmetrical case, both eigenfrequencies will be present.

IV. Simulation Setup

This section briefly describes the precautions for the simulations in the different tools.

A. *PSCAD*

The model in PSCAD has been implemented using only standard models for the components. The single cage induction generator was modeled using a double cage model and setting the impedance of the second cage to a very large value. In the standard 3-phase 2-winding transformer model only ± 30° phase shifts can be selected. Other phase shifts can be obtained using 3-line representation of the models, and connecting the transformer output phases suitably to following component input phases.

The program is only capable of doing EMT simulations, and a simulation must either be started from zero on all states or a snapshot. To have a stable steady state operation point, a 10 seconds simulation is performed before applying the fault.

The step size can be chosen arbitrarily, but is fixed during the simulation.

B. *SIMPOW*

In SIMPOW, the model could also be implemented using standard components. The voltage source was, however, modeled with an equivalent synchronous machine connected to a defined infinite bus.

The program can perform EMT simulations, balanced and unbalanced RMS simulations, and load flow analyses. The step size can be adapted during the simulation, but this feature was disabled during the presented simulations in order to get a fair comparison to PSCAD.

Unlike PSCAD, SIMPOW can be started from a stationary point, found with a load flow calculation.

C. PowerFactory

The features of PowerFactory are similar to the features mentioned in the section about SIMPOW. However, the multi mass model had to be implemented in a user-defined model, using the Fortran like DIgSILENT Simulation Language, and the voltage source was modeled with an ideal Thevenin source.

D. PSS/E

The induction generator is implemented in PSS/E using CIMTR3 model. The model represents the flux transient in the rotor with an additional state variable to handle large frequency deviation in the system.

The dynamic impedance, ZSORCE, for this model is set equal to the machine transient reactance [14][15]. This means that the stator resistance is not concidered in this model.

The shaft model used in this simulation is not yet available in the tool's built-in library; hence a user-defined model was developed instead. The user-defined shaft model is represented as a governor providing mechanical torque to the generator.

The Thevenin equivalent of the infinitive generator is approached by GENCLS model, which represents a generator with a constant voltage behind the transient reactance. The generator model is rated at 100 MVA with high inertia constant to assure its stiffness.

PSS/E's two-winding transformer model in this simulation allows representation of two impedances only e.g. the magnetic impedance and the line impedance. The latter is defined as the measured impedance of the transformer between the buses to which its first and second windings are connected.

E. General

The simulations were performed in all tools with 30° phase shifts in transformers instead of the 150° phase shifts of the benchmark model transformers. However, this does not influence the simulation result magnitudes compared in this paper.

The EMT simulations were performed with a fixed step size of 10 µs and the data was saved with a sampling time of 100 µs. For the RMS simulations, a simulation and sampling time of 5 ms was used in SIMPOW and PowerFactory. In PSS/E 10 ms was used for both simulation and sampling. However, PSS/E performs two concurrent calculations at the same time step right before and after an incident, which displays a voltage rise as a vertical line. The 3-phase short circuit is implemented as three independent ground faults, which are cleared at the first zero crossing. This is the default behavior in SIMPOW and PowerFactory, but not in PSCAD.

V. Results

A. Repeated 2-phase to ground short circuit on Bus 1

The first simulation is a 2-phase short circuit to ground fault on Bus 1 (50 kV side of the distribution transformer). The fault occurs at t = 1 s, has duration of 100 ms and is repeated after 300 ms. This is one of the faults described in [16] where the turbine must stay connected.

Fig. 6 shows the voltage at the generator terminals calculated with the unbalanced RMS algorithm using PSS/E, PowerFactory and SIMPOW. PSCAD does not have this feature. It is seen that the voltage drops to about 0.35 p.u. and recovers approximately 0.2 s after the fault is cleared. The course of the repeated fault looks similar to the course of the first one. In this figure, both the positive sequence and the negative sequence component are shown. The zero sequence component is zero as stated in chapter III, Fig. 4. The negative sequence is an expression of the voltage variation due to the unsymmetrical fault; hence, the negative sequence causes a 100 Hz variation in the dynamic amplitude plots. The negative sequence component is not available for the user in PSS/E.

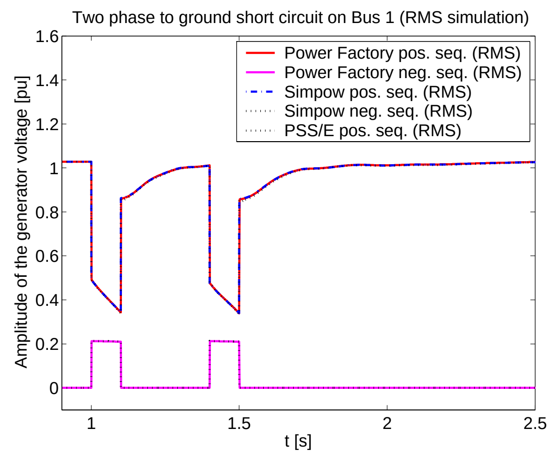

Fig. 6 Generator voltage during both 2-phase to ground short circuits

RMS calculation is mainly used for transient stability considerations; that is overspeeding which is analysed as a dynamic phenomenon, and voltage stability which is a quasi-dynamic phenomenon. For the overspeeding of the machine, and hence the electrical torque calculation, it is generally assumed that the RMS calculation introduces conservatism in the calculations for symmetrical faults, which is also the justification of using RMS calculation in transient stability studies. The dynamic calculation is important in transient angle stability as the acceleration of the machine determines the abilities of the generator to maintain synchronism. For voltage stability the stationary reactive power component is more important, since it defines the stationary loading of the connecting lines, however, the dynamic simulation will determine if a new and undesirable steady state operating point is reached.

In addition to the RMS voltage plots, EMT calculations for PSCAD, PowerFactory and SIMPOW are included in the plots following.

A zoom to the voltage in the beginning of the first fault with the outputs of the EMT simulations added can be seen in Fig. 7. Immediately after the short circuit the voltage amplitude drops to practically zero. After this some oscillations are seen. A frequency analysis of the plotted magnitude shows that the resonant frequency of about 290 Hz is folded with the 50 Hz fundamental frequency, which gives a contribution at about 240 Hz and 340 Hz. This oscillation decays rapidly. Another dominant frequency is 100 Hz, which is caused by the negative sequence due to the unbalance.

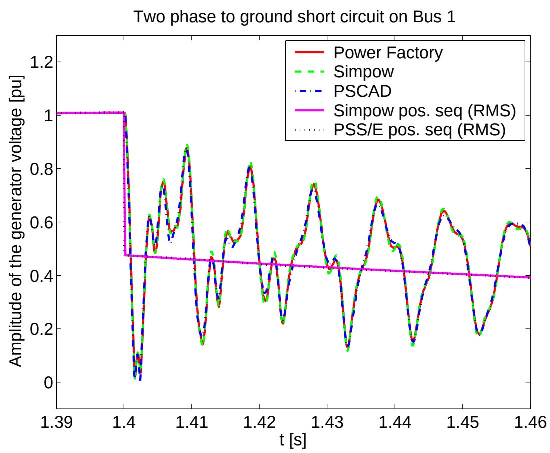

Fig. 7 The voltage in the beginning of the second fault

The voltage in the end of the second fault can be seen in Fig. 8. Before the clearance a large 100 Hz component is still there. After the fault is cleared, only the eigenfrequency folded with 50 Hz can be seen. Making an FFT analysis of a single phase reveals that the oscillation frequency is close to the 263 Hz calculated in (4).

There is an almost exact match between the output from PowerFactory, SIMPOW and PSS/E for RMS calculations. SIMPOW and PowerFactory also have an almost exact match for the EMT calculations. The fast oscillations after the clearance are more damped in the output from PSCAD than in the outputs from the two other tools. It was assumed that this difference is caused by different integration algorithms. For verification the damping factor of the solver in PowerFactory was reduced from 0.99 to 0.001. This means that the solver uses a damped Newton solution method rather than an undamped solution. With this change the output from PowerFactory was closer to the output from PSCAD. Further investigation on the solver influence in the high frequency region is, however, needed.

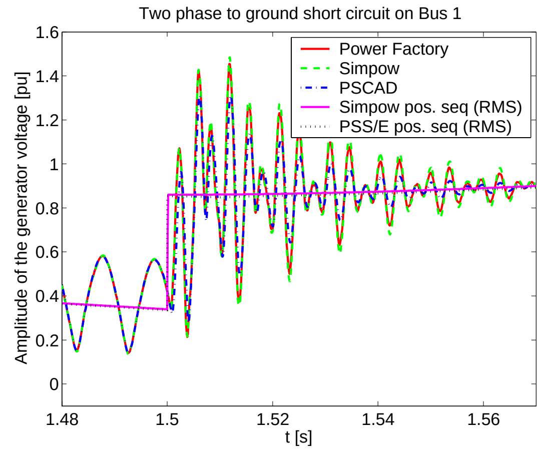

Fig. 8 Generator voltage after the second 2-phase to ground short circuit

Fig. 9 gives the course of the generator current during the first short circuit, since this is where the largest current peak is reached. During the short circuit two major frequencies in the amplitude of the current magnitude can be observed: 50 Hz due to the DC component of the stator flux transient and 100 Hz due to the negative sequence component. Again, there is almost 100 % agreement between SIMPOW and PowerFactory. The transient DC current calculated by PSCAD is slightly larger than the one calculated by Simpow and PowerFactory, but that is within 1%. The damping of the high frequency oscillations after the clearance is also larger in PSCAD.

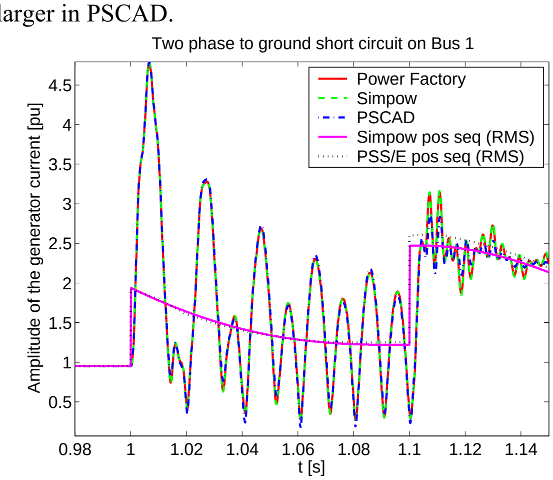

Fig. 9 Generator current during the first 2-phase to ground short circuit

The first current overshoot of the EMT simulations is approximately 2.5 times as large as the overshoot of the positive sequence current from the RMS simulation of PSS/E and SIMPOW. For systems equipped with rapid protection relays, the RMS simulation is not adequate. During the fault, there is a very good agreement between SIMPOW and PSS/E, but when the fault is cleared, PSS/E calculates a slightly higher current than SIMPOW. The reason for this is probably the difference in speed, seen in Fig. 12.

Fig. 10 shows the torque during the fault. It can be seen that the electrical torque from the EMT simulation has the same average as the output from the RMS simulations. The 100 Hz component, introduced by the negative sequence current will therefore only have a minor influence on the acceleration of the rotor. Just after the occurrence of the fault, the torque from PSS/E is slightly lower than the torque from the RMS simulation in SIMPOW, and after the clearance, it is slightly higher. The only reason for these small differences is the model implementation of PSS/E compared to PowerFactory and SIMPOW. The EMT simulations show a very good agreement. Again, the high frequent oscillations are more damped in PSCAD than in the other tools.

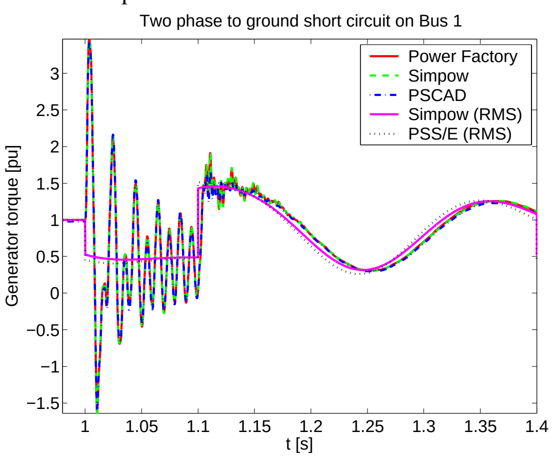

Fig. 10 Electrical torque during the first short circuit

Fig. 11 presents the generator speed during both faults. It can be seen that the speed does not stabilize between the two faults. Consequently, the generator speed reaches a slightly higher level after the second fault than after the first fault.

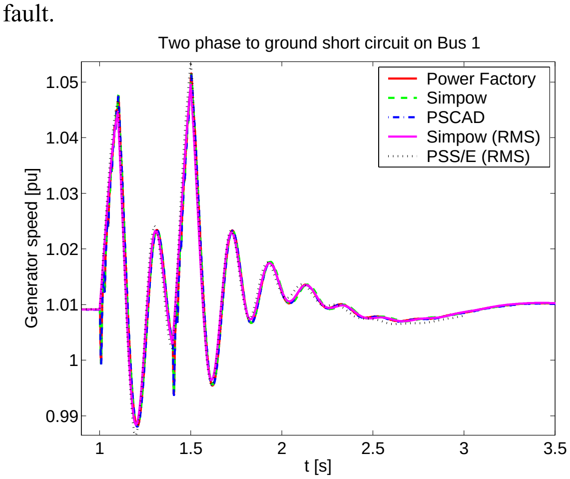

Fig. 11 Speed during both 2-phase to ground short circuits

Fig. 12 reveals differences between the speed from the RMS simulations and the EMT simulations. This is expected, since the RMS model does not include the stator flux dynamics, which means that the first positive torque, seen in Fig. 10 is not included in the RMS simulation, which causes it to speed up more rapidly than the EMT simulation. The 100 Hz oscillation in the torque can also be seen in the speed. Just before the fault is cleared, the speed in EMT simulation reaches 1.048 p.u., where as the speed in RMS simulation from SIMPOW reaches 1.045 p.u., and in PSS/E 1.047 p.u. The maximum of the EMT simulation is of course affected by the 100 Hz oscillation, which was at its maximum, when the fault was cleared. The difference between the speed output from SIMPOW and PSS/E was expected due to the different torques. There is a good agreement between the three EMT simulations which was also expected due to the similar torques.

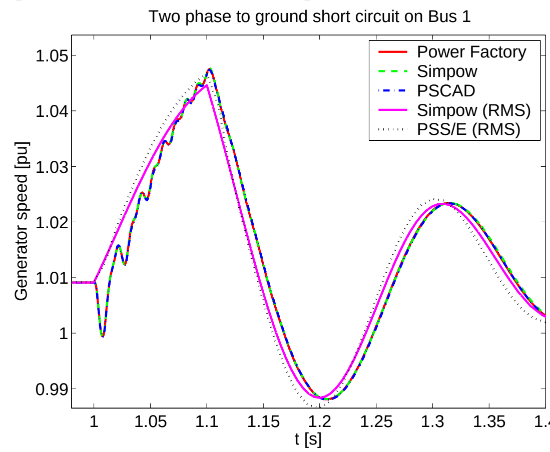

Fig. 12 Generator speed during the second 2-phase to ground short circuit

B. 3-phase short circuit on Bus 1

The second simulation is a single 3-phase short circuit with duration of 100 ms at Bus 1. According to [16] the wind turbine/park must stay connected during this fault. Since PowerFactory, SIMPOW and PSCAD have shown very similar results in the unsymmetrical case, which is considered the more complicated case to simulate; only PowerFactory is used for the symmetrical EMT simulation. For comparison with PSS/E, a balanced RMS calculation from PowerFactory is also included.

After the short circuit, the voltage shown in Fig. 13 goes down to about 0.11 p.u. It recovers after about 0.2 s. The reason for the steeper fall and rise from the PSS/E, is that it saves two values for the same time, when events occur, which is not the case for PowerFactory. Considering that difference there is a very good agreement between the two outputs. The voltage of the EMT simulation include oscillations at the eigenfrequency, 290 Hz ± 50 Hz and also 600 Hz due to the different instantaneous current in the phases, when the fault occurs. After the short circuit is cleared, the 600 Hz component can no longer be seen. This is probably due to the fact that the fault currents are terminated at their zero crossings.

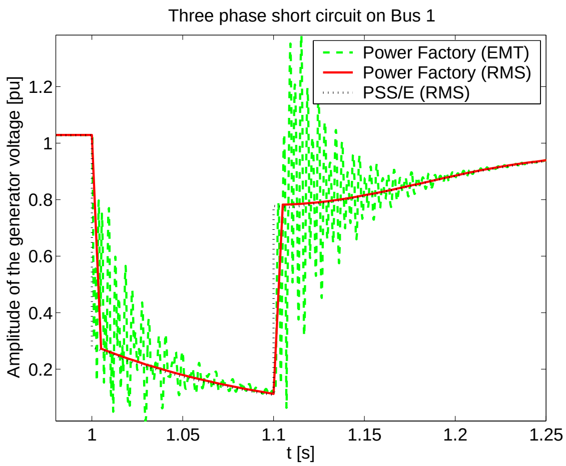

Fig. 13 Generator voltage after the 3-phase short circuit

Fig. 14 presents the current during the short circuit. The 50 Hz component has approximately the same amplitude as in the unsymmetrical case, but it decays faster. Since the fault is symmetrical, the current does not contain any 100 Hz component. During the fault there is a good agreement between the RMS outputs from PSS/E and PowerFactory, but after the clearance PSS/E simulates a slightly larger overshoot than PowerFactory. Compared to the unsymmetrical case, the RMS simulations in the symmetrical case give a better estimate of the current overshoot.

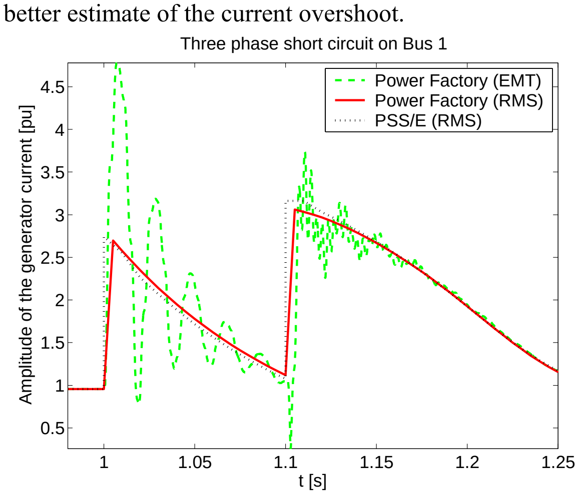

Fig. 14 Generator current after the 3-phase short circuit

The simulated speed, shown in Fig. 15, reaches a slightly larger maximum value for PSS/E than for PowerFactory. It also seems that the mechanical frequency from PSS/E is a little higher than the one from PowerFactory. This can be due to differences in the implementations of the built-in models.

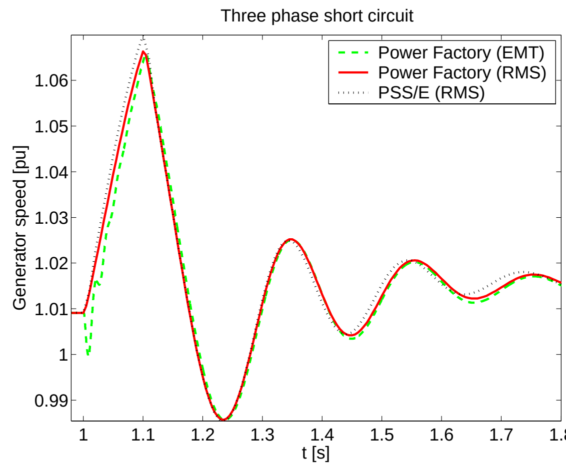

Fig. 15 Speed after the 3-phase short circuit

VI. Conclusions

1) Faults: The following observations regarding behavior of the different fault types have been made during the simulations. It should be noted that they only apply for the simple test system.

The 3-phase fault is the most severe fault regarding over speeding and voltage drop. However, regarding the short circuit current of the generator, the maximal peak current is approximately the same for the 3-phase and the 2-phase to ground fault. But where the current in the symmetrical case rapidly decays, the remaining flux in the generator causes the current in the unsymmetrical case to converge to a certain level. This should be taken into account when adjusting the relays.

Regarding over speeding, the repeated fault is a little more rigorous than a single fault, since the speed does not stabilize between the faults.

2) RMS Vs EMT: The RMS simulation gives a good estimate of the speed. In the 3-phase case, the RMS simulation estimated a marginally larger maximum speed than the EMT simulation. In the 2-phase to ground case it was the other way around.

The current peak, caused by the DC transients, is not considered by the RMS simulations.

3) Comparison of the programs: PowerFactory and SIMPOW show practically identical results both for the RMS and for the EMT simulations. PSCAD simulates slower decaying DC current transients and more damped 300 Hz oscillations. The last difference could be due to different solver algorithms.

The RMS simulation results from PSS/E deviate marginally from the outputs of SIMPOW and PowerFactory. Specially, the generator speed from PSS/E is estimated higher than by the other tools. It is assumed that this deviation is due to a different implementation of the model in PSS/E.

Concerning RMS simulation, unsymmetrical faults can be simulated in PSCAD, SIMPOW, PowerFactory and PSS/E. In PSS/E, however, only the positive sequence voltage and current are provided. It is therefore not possible to derive the maximal load of a single phase.

Generally, all four programs can be used for calculation of voltage and transient stability during symmetrical and unsymmetrical faults in a system like the test system used in this paper. If the dynamic simulation includes excact settings and operation of rapid relays responding to transients, EMT simulations – which cannot be carried out in PSS/E – are needed. Especially for unsymmetrical faults this should be considered, since the current decays more slowly than in case of symmetrical faults.

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IX. Appendix

A. Parameters for the test system

Component	Symbol	Value	Unit
50 kV grid			
	U_{th}	50	kV
	R_{th}	2.1156	Ω
	X_{th}	8.2998	Ω
50/10 kV Transformer			
	S_n	16	MVA
	U_p	50	kV
	U_s	10.5	kV
	R_p	0.4052	Ω
	X_p	7.655	Ω
	X_m	19530	Ω
	R_s'	0.4052	Ω
	X_s'	7.655	Ω
	Cou-pling	YNΔ5 = -150	deg
Short Circuit			
	Z_{sh}	1.00E+06	Ω
	Z_{sc}	0.00011	Ω
10 kV Collection cable			
	C_1	1.58	µF
	R	0.7568	Ω
	X	0.4473	Ω
	C_2	1.58	µF
10/0,96 kV Transformer			
	S_n	2	MW
	U_p	10.5	kV
	U_s	0.96	kV
	R_p	0.2756	Ω
	X_p	1.654	Ω
	X_m	6890	Ω
	R_s'	0.2756	Ω
	X_s'	1.654	Ω
	Cou-pling	ΔYN5 = -150	deg
Wind turbine generator			
	S_n	2.3	MVA
	U_n	0.96	kV
	N_o	1500	rpm
	R_s	0.004	Ω
	X_s	0.05	Ω
	X_m	1.6	Ω
	R_r'	0.004	Ω
	X_r'	0.05	Ω
Wind turbine capacitor bank			
	C	1333	µF
	R	0.003	Ω
	Conn.	Δ	
Mechanical System			
	I_{wtr}	4.18E+06	kgm^2
	I_{gen}	93.22	kgm^2
	k_{ms}	8.95E+07	Nm/rad
	f	80	